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Enhancing Integrative Capabilities through Lean Product and Process Development

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Abstract

To survive in today's hostile business environment, companies must constantly introduce new products and adapt their strategy to change. Managing product variety may therefore be considered as an important competitive factor. However, this requires resources in terms of people, equipment, inventory and raw material—all of which go against a Lean strategy. Mastering complexity becomes increasingly important in several industries, and companies must find a way to balance between lean and offering product variety. As robots become less expensive and more 'intelligent', in combination with more advanced CAM solutions, automated assembly may become beneficial at much lower quantities than in the past. Also, development of new manufacturing methods may enable new product designs, and vice-versa. In this emerging paradigm shift—also referred to as Industry 4.0—companies must enhance their integrative capabilities and facilitate knowledge sharing between product engineering and production to sustain competitive advantage. This paper discusses organizational capabilities and tools required to enable transformation into Industry 4.0. Literature on Integrated Product and Process Development (IPPD), Concurrent Engineering (CE) and Lean has been studied. This state-of-the-art is seen in connection with efforts made in a research project with the goal to increase competitive advantage by leveraging capabilities in automated manufacturing of large and complex products—a manufacturing context that is regarded as difficult to automate in an economical way. The results show that investing in the latest manufacturing technology alone will not provide the capabilities required. It is also necessary to invest in people skills, knowledge and organizational learning. Process design and design-for-automation must be considered already from the conceptual product design to avoid expensive re-designs and design loops. The use of physical and virtual demonstrators proved to facilitate an efficient and effective design process.

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1. Introduction

1.1 Background

Today, the global economy is characterized in terms of rapid technological changes, customization and the need for fast time to market. Value creation, competitiveness and hence sustainable growth are dependent on development and utilization of new technology. To survive companies must constantly introduce new products, processes and technologies faster than their competitors do. The pressure on the designer increases as the product life cycle shortens, and the complexity of modern products requires the competency profile of the engineer to be T-shaped (1), emphasizing interdisciplinary skills (2).

To keep phase with customer demands, businesses have had to slim production to bare bones. For many company`s this has involved relocation of production or even outsourcing of capabilities (3). Further, leveraging product variety as a competitive strategy requires more designers and engineers, more components and raw material, more changeovers in production lines, higher inventory levels, more equipment, etc. (4)—all of which go against a lean strategy.

However, forward-looking businesses increase the level of in-house production by investing in advanced production technology, reducing labour to a less significantly portion of the production cost. Such investments in highly automated and

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IT-driven production are often referred to as Smart Manufacturing, which is a concept that marries information, technology and human strength (3). These new production methods facilitate a lean way of thinking, which changes the premises for competition and consequently the fundamentals for a company's business system.

Advancement in technology often requires changes in the organization to achieve productivity gain (5). This includes both investments in terms of capital and acquiring knowledge (5); i.e., leveraging R&D to keep phase with technology and be able to offer integrated solutions (2).

1.2 Industry 4.0

The Industry 4.0 concept is representing a paradigm shift, where physical objects are seamlessly integrated into information networks (2; 6). This may enable improved infrastructure for sharing information where design, product development and manufacturing are closely integrated. When combined with increased digitalization, the concept may open up radically new ways of designing products and manufacturing systems. The dominant technologies within Industry 4.0 are expected to be IT, electronics and robotics (2), and may facilitate improved manufacturing processes allowing high levels of automation as well as engineering, material usage and life cycle management.

External drivers such as introduction of new materials and technologies influence the way products are designed and exploited. Design is often constrained by the fabrication method such that a new manufacturing technology will create a technology push in design. An example is 3D printed parts, which can enable lighter parts and improved material utilization if the design fully utilizes the opportunities of the processing process.

Traditional automation has not been able to offer the flexibility and agility required for rapid configuration for new product demands (7). However, the development of 3D CAD/PLM software, computer vision, sensor technology and new programming methods may increase the use of robots in the coming years, thus making automatic assembly economically feasible at much lower quantities than in the past.

1.3 Motivation

Rolls-Royce Marine (RRM) has proven capabilities in system integration, ship equipment and design (8). RRM has a varied product portfolio consisting of several large and complex products, typically produced in volumes of less than 1,000 units p.a.. RRM's products are typically customized, engineer-to-order type products. To sustain competitiveness more cost-effective engineering and manufacturing methods are required. As a result, RRM together with research partners has invested in a research project named Autoflex. The intention is to determine capabilities of automated assembly of large and complex products that require close fit-up tolerances. The case is a Permanent Magnet Tunnel Thruster (PM-TT), which is a new product from RRM that fits well into the description above. Competitive production of the PM-TT calls for significantly more effective production methods than those used in the pre-series.

The PM motor consists of two main parts, stator and rotor, which are built up by more than 100 components. The stator carries a number of electrical coil windings, and the rotor is fitted with strong permanent magnetized magnets. It has a propeller diameter of 1,600 mm and a total thruster weight of more than 7,000 kg.

This paper addresses the challenge of developing and introducing new technology in a company that is producing products in a high-cost country, seeking to explore the following topic: How to enhance a company`s integrative capabilities, facilitating changes required to enable an emerging transformation into Industry 4.0? More specifically, the objective is to identify the challenges of product and process development of complex products for a competitive world-market with basis in Norway.

The reminder of this paper is organized as follows: Section 2 presents relevant literature on design development processes. Section 3 addresses the problem in light of the literature presented in Section 2 and with efforts made by RRM to succeed with automated assembly in a high-mix, low volume context. Finally, Section 4 presents concluding remarks.

2. Theoretical Background

2.1 Product Design Processes

For a company to convert its technology and ideas into new products that meet customer requirements and the strategic goals of the company, a product development system that effectively integrates people, processes and technology is needed (9; 10). Methods that lead to shorter development time, faster product realization, reduction of product development cost and improved quality must be leveraged.

Integrated Product and Process Development (IPPD), Concurrent Engineering (CE) and Lean Product Development all aim to speed up innovation processes using somewhat different approaches. What all these 'schools' have in common is to facilitate design decisions, tackle conflicting goals and avoid costly redesign and unpredicted problems or compromises that degrade the final product (11). While CE has its roots in western product development, Lean has been developed from the Japanese perspective, i.e. the Toyota Production system (12).

<u>Concurrent Engineering (CE)</u>

The design and development process can be more efficient by executing working steps in parallel (13). A working method emphasizing this is CE. According to Winner et al. (14) "*Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life-cycle from conception through disposal, including quality, cost, schedule, and user requirements.*" CE puts a huge emphasis on multi-disciplinary teamwork, and has gained high acceptance and represent now the industry standard.

The challenge associated with CE is that—as the design concept passes between the different functional groups for assessing feasibility—every change causes a myriad of changes, analyses, and hence additional communication demands (15). These design iterations take time and resources, and in many cases the product design is transferred into a suboptimal solution as the team typically runs out of time. Further, there is a risk of starting with a design and a process that is not the best starting point for the solution. This may lead to iterations over a solution that is non-optimal (point-based approach) and the time spent late in the process is characterized by find-and-fix it (15; 10).

Front-loading of the product and development process by considering several solutions before narrowing down is termed Set-Based Concurrent Engineering (SBCE), Sobek et al. (15). SBCE is claimed to lead to more efficiency and improved product integration later in the process. Instead of selecting and refining one concept, SBCE consider a broader range of concepts, excluding those solutions that are not sustainable by eliminating alternatives step by step. The paradox (10) is that this will delay some decisions, but in return, the whole process may be faster and more efficient. Moreover, a set-based approach is beneficial when the cost of rework is high (16).

<u>*Integrated Product and Process development (IPPD)*</u>

Development of a new product may demand new processes such as manufacturing, logistics and data collection (17). The term IPPD is defined by the Department of Defense (DOD) (17) as; *"a management technique that integrate all acquisition activities starting with requirements, definition through production, fielding/development and operational support in order to optimize the design, manufacturing, business and supportability processes"*. Further, IPPD emphasizes the use of design tools such as modelling and simulation to develop the product and process concurrently (17; 11). IPPD is a broad concept where a multidisciplinary team, also referred as Integrated Product Teams (IPT), is responsible for delivering a defined product and/or process (17). The interactions within the design process are rapid, highly concurrent, interactive and iterative (11), emphasizing customer input and creating more manufactural designs (18).

An iterative design strategy is attractive when the quality of the first guess is high, cost of re-work is low and feedback is fast (16).

<u>*Lean Product Development*</u>

Lean is often associated with production of physical products where the aim is repetitive operations achieving high quality outputs at the minimum cost and time; i.e., maximizing customer value while minimizing waste (19). *Lean product development* is a total philosophy suitable to improve efficiency in product development with basis in customer value. Several sources in the literature have discussed lean in the new product development (NPD) process (20; 21; 10; 22). Compared to CE and IPPD, lean product development has a strong focus on value and waste (23). However, compared to shop floor lean, becoming "lean" is more associated with increasing value than removing waste in lean NPD (20).

To succeed, however, creating the right culture, strategy and environment is just as important as implementing lean tools and techniques. Lean product development requires a cultural transformation into a learning organization (9). According to Karlsson & Åhlström (22) success requires employing interrelated techniques as elements of a coherent whole.

It is important to initiate and execute value-creating activities with the correct information input. An important principle in *innovative* lean development (21) is the use of rapid learning cycles as a short burst of learning. Prototypes enable rapid learning and minimize mistakes as well as integrate different functions. However, prototypes used for rapid learning are only feasible when developed quickly and inexpensively. By combining CAx technologies and Virtual Reality (VR), prototypes with high 'functionality' can be produced faster and cheaper than before (24; 16).

2.2 Supporting tools in the product design process

CE, IPPD and *lean* NPD can enhance a company's dynamic capabilities. However, what actually happens within that process or structure is dependent on the activities and how they are executed. In addition to creating the right culture, there is a need for tools and techniques that support activities. This requires subsystems that are fit for purpose, highly efficient processes are of no use if the people does not possess the skills required (10). Designers must be creative experts, correctly timing the application of tools with input from the right participants in the project (25). This may increasingly withdraw designers from traditional fields of expertise as they must both execute and manage the design process considering viewpoints from several stakeholders. Here, design guidelines, procedures and evaluation tools are useful support. These embody the CE philosophy of considering the downstream impact of decision-making (26; 27; 28).

The main sources of design guidelines include the literature, the direct experiences of practising designers and the established design practices in engineering organisations (26). The most common concepts are design for manufacturing (DFM) and design for assembly (DFA), which provides designers with tools to evaluate design-decisions and involve simultaneous considerations of design goals and manufacturing 'constraints' (29; 27).

Eskilander (30) presents a method for designing products for automatic assembly (DFA2) at both part and product level. DFA2 is a set of structured design rules with a quantitative scoring of the product design indicating how "good or bad the design is" combined with qualitative evaluation criteria also giving information on how to design for automated assembly.

One way of creating the strategic, flexible product design required to allow product variation without changing the overall product design each time a new variant is introduced, is to establish modular product platforms (31). Modularisation offers increased use of standard parts, and the possibility of standardized interfaces and components, enabling standardization of manufacturing processes and tooling. However, a risk associated with modularisation is compromising product functionality. The key is matching the solution spaces of product and production design (32).

3. Discussion

3.1 The Autoflex project

The literature presented in Section 2 will now be seen in connection with efforts made in a research project named Autoflex. The underlying goal of the project was to achieve cost-effective manufacturing of low volume, complex and heavy products in high cost countries. The case product, PM-TT is a large and complex product with tough requirements for tolerance design and strict requirements to operating life. The original design of the PM-TT requires a high degree of manual labour operations and it was early on identified that automation would not be cost efficient without modifications to the existing design.

By combining design-for-automation and state-of-the-art production technologies the project has delivered a physical demonstrator in only two years proving fully automated assembly of the PM-TT rotor. Also a virtual demonstrator of the automated assembly process for PM-TT stator has been developed. The project has introduced new methods and guidelines for engineering and development of large and complex products produced at low volume.

3.2 Enhancing the company`s integrative capabilities

A plant cannot be fully competitive by only improving operations if the design is defective (29). The design solution must not only satisfy the quality and functional requirements of the product, it must also meet certain specifications for fitting the manufacturing process within the company. On the other hand, Koufteros et al., (33) argue that excellence in product development can just as easily be eroded by manufacturing weaknesses.

The key to offer competitive solutions in the market place is considering product, people, process and tools/technology as a total system. In this perspective it is important to invest in knowledge and organizational learning in a strategic perspective. For example, buying a robot is easy compared to leveraging the people skills for incorporating it in the production environment in the most beneficial way for the company.

In the Autoflex project, automation knowledge was leveraged from external experts and combined with internal expertise in products and technology. This ensured a team with multi-disciplinary skills possessing knowledge of the technologies required to develop an automated solution for the PM-TT. Weekly meetings and close dialogue ensured that functional requirements were balanced manufacturing solutions—and vice versa.

When automated assembly of PM-TT first was investigated, the findings indicated increased factory footprint, large robots and significant investments for handling part size. The efforts made to make automated assembly cost-efficient, triggered re-design and new thinking; e.g., a large component of the PM-TT was divided into separate modules, which facilitated the use of standard robots with much less space requirements. This is a good example of manufacturing constraints creating a demand for innovation. According to Schipper & Swets (21), defining the gap between the problem and solution identifies where innovation is needed.

Sobek et al. (15) emphasized SBCE on product concept level. In Autoflex, SBCE has been applied on business level, re-designing the product and integrating verified solutions with existing product platform. Since PM-technology is relatively new to RRM and the product has a complex functionality, it was necessary to verify functional requirements with a non-optimal production process to avoid too many variables at the same time. However, driving technology or manufacturing too far without the other factors creates an investment risk. This is particularly important for complex products since this often requires dealing with a high level of uncertainty and significant investment costs. Developing the conventional design in parallel (set-based approach), was demanding yet necessary, and searching for the optimal solution required several iterations.

To narrow down solutions one can use multiple learning cycles as emphasized by *innovative* lean development (21). However, learning cycles can be costly when designing complex products since physical prototypes often are expensive and time consuming. In Autoflex, simple demonstrators, both physical and virtual, were used to verify design changes before a final more comprehensive prototype was tested. Simulation of the assembly process based on the CAD model enabled testing before design was released and any expensive equipment was purchased.

The use of simulation enables lean decision-making throughout the development process. The lead time from design to verification of the assembly process can be reduced by virtual manufacturing technologies in combination with automated programming methods from CAD models. A demonstrator of an automated assembly process for the PM-TT stator was programmed and simulated based on the CAD model. It was experienced that the frequency of design iterations increases as one iteration can be performed in a fraction of the time and cost compared to an iteration on a physical prototype.

An animated movie, presenting the project vision, was used when starting up the project to ensure that the multidisciplinary team had a common understanding of the project task. This ensured strategic information input facilitating concurrent activities (20).

Terwiesch et al. (16) argue that neither a set-based nor an iterative approach are superior over the other. What influence trade-off between set-based and iterative strategy is; quality of educated guesses, the engineering change support process and the exchange of information regarding interdependencies between components, and what kind of changes are expected to cause substantial work.

3.3 Guidelines and tools enhancing integrative capabilities

The Autoflex project has changed the mind-set of manufacturing in RRM towards developing the product and the automation process in parallel. One main argument is that relative small changes to the product design can have a huge impact on rational production. Design-for-automated assembly led to simpler product and production methods. A direct result of the re-design is that the automated process time is reduced to a fraction of the time compared to the initial manual process.

When aiming to utilize new manufacturing technologies, as the case in Autoflex, the design of the product, the facility, workstations and equipment are all important. One important experience is that process design, and design-for-automation must be considered already from the concept design to avoid expensive re-designs.

A challenge in low-volume production is that there are fewer parts between which development cost can be distributed. Hence, the cost of material and labor is weighted less important than in high-volume production where significant resources are commonly used on tooling, manufacturability and engineering (34).

In Autoflex, re-designing the product was the key factor to enable cost-effective automated assembly of the PM-TT. For example, design of a part requires designing the gripping tool used in production. If considered early, one can reduce the cost of the tool by designing appropriate geometry and surfaces of the part for gripping. Moreover, modeling the assembly solution at an early stage led to re-design of bolt holes to avoid collision between mounting tool and the product.

The Autoflex project has also brought intelligence into the assembly process. Examples are advanced use of sensors (3D vision and force-feedback) that compensates for tolerance in the gripper (and the robot), enabling assembly with close fit-up requirements.

Automation usually requires high volume of standardized parts. Modularization and standardization require less flexibility in the production system. In Autoflex, this resulted in reduced part count and operations; e.g., by integrating dowel pins as part of component. Another simple example is to have the same amount of bolt holes on a single component, instead of having products with different number of screws. In addition, standardization of screw dimensions allows one tool and one feeder to be used.

Design guidelines can be useful to establish best-practices and a repository of design tools. The project has provided rich data and information for developing guidelines for automated manufacturing. These guidelines can be useful in the further work of developing the complete PM range and help identify interfaces between process and design. Such guidelines would be a good starting point for utilizing the production system and achieve higher volume. Care should be taken in preventing that standardization and modularisation reduce product functionality, especially for complex products (35). Moreover, too much focus on standardization and modularization may be a hindrance to innovations (36).

Design is limited to the way the product is made. However, a company`s ability to absorb new technologies should not be limited by its current capabilities when designing a new product and the production process. The designer must be aware of internal workshop capabilities, as well as the ones of sub-contractors and materials suppliers. For example, the robots lifting capacity will impact the size and weight of both the product and associated production equipment. This will create trade-off issues, such as designing smaller/lighter components or investing in larger robots as in the case of Autoflex. Therefore, the development of design guidelines cannot only be based on general principles found in the literature, such as design principles for automated assembly by Eskilander (30), but also on the specific production context.

4. Concluding remarks

To sustain competitive within the emerging industry paradigm shift denominated Industry 4.0, there is an additional need to consider manufacturability also for complex products produced in low-volumes. A lessons taught from the Autoflex project is that investing in the latest technology alone will not provide the capabilities required; it is also necessary to invest in knowledge.

The use of virtual manufacturing and process simulation increases the frequency of design iterations in the development process and may reduce the verification time and cost significantly. Further, this facilitates a leaner product and process development enabling corrective actions to be taken before design release for production and the solution is still on the drawing board.

Based on experience gained in the Autoflex project, we suggest that there are two directional paths for a company to enhance its integrative product development capabilities:

(a) to leverage agile strategies for Integrated Product and Process Development (IPPD);

(b) to frontload resources in early phases when cost of learning is low and the design space is wide, using methods such as SBCE.

In Autoflex, the key was to master both a) and b) to ensure that neither manufacturing nor technology was driven too far without support in the other. Moreover, this working method ensured a strong integration of manufacturing and product engineering. This enabled the company to choose problem solving strategy based on the complexity of the task, the technical characteristics and the problem-solving capabilities of the organization.

Within the Industry 4.0 concept, a company must be able to absorb new technologies that change the premises for competitive production. This implies that a company must strengthen its absorptive capabilities to avoid being boxed in by current capabilities for designing a new product and its belonging processes.

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